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CONTRIBUTION OF ANTHROPOGENIC CLIMATE CHANGE TO APRIL–MAY 2017 HEAVY PRECIPITATION OVER THE URUGUAY RIVER BASIN

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Anthropogenic climate change has increased the risk of the April–May 2017 extreme rainfall in the Uruguay River basin, which has caused extensive flood and major socioeconomic impacts, by at least twofold with a most likely increase of about fivefold.

INTRODUCTION. The Uruguay River is a transboundary river of great economic importance in South America. Its headwaters lie in southern Brazil, the middle reach forms part of the Brazil–Argentina border, the lower reach forms the Argentina–Uruguay border, and it then empties into the La Plata River with a catchment area of 3.65×10^5 km^2. The river basin has a temperate climate with annual mean precipitation of 1,750 mm with little seasonality. During the late twentieth century, the Uruguay basin had a positive trend in precipitation (Barros et al. 2008) and streamflow (Pasquini and Depetris 2007). Based on hydrological modeling, Saurral et al. (2008) attributed the 1960–2000 streamflow trend mainly to the increase in precipitation rather than land cover change. The upper Uruguay River catchment has relatively high relief, low soil storage capacity, and land use is mostly pasture and cropland. Therefore, the catchment has a fast hydrologic response in which flood occurrence is more dependent on meteorology than on initial conditions of soil moisture and flow (Tucci et al. 2003). A cascade of hydroelectric dams is used for flood control operations. However, when more persistent and intensive rainfall systems develop over the upper catchment, the high soil moisture, fast rainfall runoff response, and limited storage capacity of reservoirs overwhelm the flood control operations and result in downstream flooding. Flood related impacts have also increased, resulting in a growing concern regarding the need to identify the causes of increased flood frequency and establish effective mitigation efforts.

Explaining the increase in flood frequency requires assessing the role of climate change in shifting the likelihood of extreme rainfall events over the catchment and building more detailed understanding of ongoing changes in the linkage between rainfall and hydrological mechanisms that cause flooding in this flow regulated catchment. To address the former, we analyzed the influence of anthropogenic climate change on the likelihood of the heavy rainfall that occurred in April–May 2017, which led to widespread overbank flooding along the Uruguay River that peaked in June, causing significant impacts such as direct economic loss in Brazil of 102 million U.S. dollars (FAMURS 2017) and displacement of more than 3,500 people in Uruguay (BBC 2017).

DATA AND METHODS. The Climate Prediction Center (CPC) Global Unified Precipitation data (Chen et al. 2008) with a spatial resolution of 0.5° × 0.5° were

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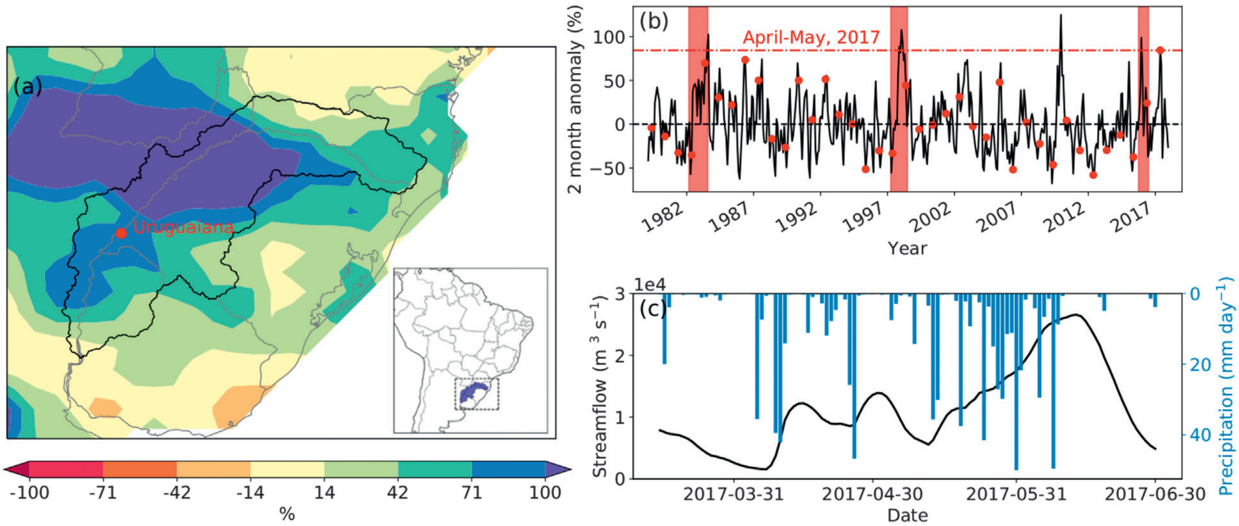

FIG. 1. (a) 2017 April and May anomalous precipitation in the Uruguay basin as percentage difference from a 1979–2013 climatology, based on the Climate Prediction Center (CPC) Global Unified Precipitation data. The gray borders indicates the geographic boundaries for coastlines, countries and Brazilian states, while black line indicates the boundaries of the Uruguay River basin. (b) Two-month precipitation anomaly related to the period of 1979–2017 as percentage difference from the 1979–2013 climatology, based on the Uruguay catchment average calculated using the CPC data (black line). Red bars in (b) highlight very strong El Niño events, where the Oceanic Niño Index (ONI) was greater than 2°C for more than 3 consecutive months; red dots indicate April–May precipitation anomaly and the red dashed dotted line the 2017 April–May anomaly. (c) Daily streamflow from Uruguaiana (black line) and daily precipitation for the average CPC data in the catchment area upstream of Uruguaiana (blue line).

used to characterize the precipitation over the Uruguay River catchment for the period 1979–2017 (Fig. 1). We applied the Met Office Hadley Centre atmosphere-only general circulation model HadGEM3-A (Ciavarella et al. 2018) at N216 resolution (approximately 60 km in the midlatitudes) to assess the influence from anthropogenic forcings. For 1980–2013 two ensembles of 15 members were used. The first ensemble ("Actual") is driven by both natural (variability in the solar irradiance in the top of the atmosphere and volcanic activity) and anthropogenic forcings [greenhouse gases (GHG), zonal-mean ozone concentrations, aerosol emissions, and land use changes], with sea surface temperatures (SSTs) and sea ice coverage from HadISST (Rayner et al. 2003). The second ensemble ("Natural") is driven only by natural atmospheric forcings, and has the estimated impact of anthropogenic forcings removed from SST and sea ice patterns using the attribution method described in Pall et al. (2011) and Christidis et al. (2013). To estimate the change in likelihood of the 2017 heavy precipitation, we analyze the extensions of these ensembles (denoted "ActualExt" and "NaturalExt") that were available from March to August 2017 with 525 ensemble members each.

The Actual and Natural ensemble members are multidecadal simulations, from 1960 to 2013, designed primarily for model validation, while the ActualExt and NaturalExt are shorter simulations with a higher number of ensemble members used for attribution assessments. The "Ext" simulations are continuations of the 1959–2013 runs, with the ensemble members increased by producing batches of members branching from the end of a single multidecadal simulation, which therefore share the initial conditions of the small size ensemble but are different in the realization of the stochastic physics (Ciavarella et al. 2018).

To establish how representative the precipitation in the climate model is for our study region we applied a nonparametric two-sample Kolmogorov–Smirnov (KS) test to verify if the CPC precipitation and the "Actual" model simulations from 1979 to 2013 were from the same distribution (Wilks 2006). Gamma distributions were fitted to ActualExt and NaturalExt to estimate the risk ratio (RR). To test sensitivity to the fitted distribution we also fitted a generalized extreme value (GEV) distribution to both distributions. Risk ratio is a metric recommended for use in attribution (National Academies of Sciences, Engineering, and Medicine 2016) to indicate the change in probability of an event with climate change, and is simply the ratio of the actual probability to the natural. Uncertainties within the simulations were computed using a bootstrap resampling method (Efron and Tibshirani 1993).

RESULTS AND DISCUSSION. The region is characterized by monthly precipitation distributed equally throughout the year, and is susceptible to floods year round. However, April–May 2017 precipitation was the largest April–May anomaly and the eighth highest anomaly for a two-month consecutive period since 1979 (Fig. 1b). It resulted from a succession of intense events from synoptic scale to mesoscale in the region (CPTEC 2017a,b). A major component was the interaction of midlatitude meteorological systems with the low-level jet to the east of the Andes that supplied additional moisture from tropical regions, enhancing the associated convection. April events enhanced the streamflow in the basin (Fig. 1c) and also led to increased soil moisture and reservoir levels. In May, more heavy rainfall over the hydrological wet conditions resulted in flooding that peaked in the beginning of June with a return period of 40 years, causing great economic impacts.

Unlike most of the large anomalies in Fig. 1b, April–May 2017 coincided with a neutral phase of El Niño. However, the austral summer of 2017 was characterized by an unusual fast warming of the far eastern Pacific, denominated by a coastal El Niño (Garreaud 2018). Generally, positive precipitation anomalies in southern Brazil are expected during El Niños (Grimm et al. 1998, 2000), which can cause significant floods (Pasquini and Depetris 2007). Because of the low streamflow in the end of March (Fig. 1c), the low soil moisture storage, and the fast response of the basin, no preconditioning of soil moisture from earlier months would have had a significant impact on the flood. However, we cannot reject the hypothesis that this El Niño increased the frequency of the low-level jet (Silva et al. 2009), which is a key component in producing precipitation in the region.

To avoid a selection effect we consider 1986 April–May precipitation as a threshold for record-breaking events. Although this was a moderate El Niño year, the 1986 flood occurred in April of that year and had similar meteorological conditions to 2017, with heavy precipitation events in the headwater of the basin during a two-month period, resulting in the second highest April–May anomaly on record for the CPC dataset with 517 mm and a positive anomaly of 73%.

At the 5% significance level, the KS test indicated that we cannot reject the hypothesis that both datasets, the CPC observations and "Actual" historical simulations (1980–2013), were drawn from the same distribution (p value = 0.9). This suggests that the Actual simulations were able to correctly reproduce the statistics of April–May historical precipitation over the catchment area of the Uruguay River (see also online supplemental material). When the same test was used to check whether "Actual" and "Natural" simulations were different, the result indicated that they were not drawn from the same distribution (p value = 0.005), suggesting a difference between the simulations over the catchment area.

The fitted probability distribution functions (Fig. 2a) indicates different shapes for ActualExt

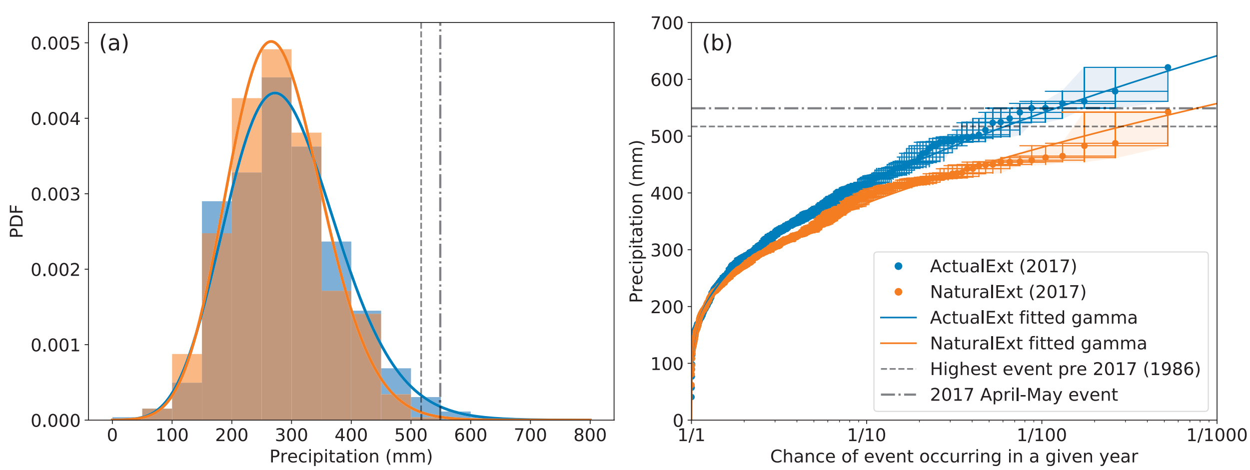

Fig. 2. (a) Probability distribution function for fitted gamma distributions of ActualExt and NaturalExt simulations of 2017 April and May accumulated precipitation in the Uruguay basin. (b) Return time for the ActualExt and NaturalExt experiments. Each marker represents an ensemble member and the blue and orange lines are the fitted gamma return period for the ActualExt and NaturalExt, respectively. The errors bars indicate the 95% confidence interval using bootstrap resampling. Black dashed line indicating the 517 mm threshold based on the 1986 event and the 2017 rainfall of 549 mm as dashed dotted line.

and NaturalExt, with a high narrower PDF in the NaturalExt world in comparison to the ActualExt world. On the other hand, ActualExt shows increased probabilities in the right tail of the distribution, indicating greater chance of extreme events due to anthropogenic forcings, such as the 1986 and the 2017 thresholds. ActualExt also shows a 61-yr return time (Fig. 2b) for the 1986 threshold while NaturalExt indicates a return period of 285 years according to the fitted gamma distributions. Furthermore, for the 61-yr return time, NaturalExt has 11% lower precipitation than ActualExt.

We assessed the risk ratio using the fitted gamma distributions for ActualExt and NaturalExt. The value obtained was about 4.6, suggesting that the chance of occurrence of a 1986-like event is about 5 times greater in ActualExt than in the NaturalExt. Uncertainty in the RR was estimated using bootstrapping. For each model ensemble 1,000 samples, with replacement, were produced and gamma distributions fitted. They were used to calculate the probability of exceeding the threshold, for both the ActualExt and NaturalExt simulations. In this case, the RR distribution had a median of 5.2 with 5 and 95% percentiles of 2.6 and 10.4, respectively. Using a GEV fit and identical methodology we find that the RR distribution was highly skewed with a median of 4.7 with 5 and 95% percentiles of 2.0 and 17.7 respectively.

The historical record of CPC alone (Fig. 1b) did not seem to foresee the anomalous event of 2017, with 13 years since 2000 experiencing close to or below average anomalies in April–May. However, the increase in probability of enhanced precipitation events in ActualExt is consistent with the findings of Soares and Marengo (2009). They investigated the South American low-level jet in a warming climate due to anthropogenic influence and found an increase in the meridional moisture transport from the Amazonian region to the south part of Brazil, where the Uruguay River basin is located, mainly because of an increased temperature gradient between tropical and subtropical South America.

CONCLUSIONS. This article examined the April–May 2017 extreme rainfall in a historical context, and analyzed the influence of anthropogenic climate change on the likelihood of such an event that led to severe flooding of the Uruguay River. We found that anthropogenic climate change has increased the risk of the April–May 2017 extreme rainfall in this catchment by at least 2 times with a median increase of about 5 times. However, when considering event attribution it is necessary to consider methodological limitations. The removal of the anthropogenic effect in the SST and SIC is a major source of uncertainty, as well as land use changes. Also, there is a need for a more thorough evaluation of the circulation patterns in the model simulations for that particular region that is beyond the scope of this paper.

Our study made reference to the 2017 flooding of the Uruguay River as the main impact caused by extreme rainfall over a two-month period. The length of the period was defined based on the prerequisite of high levels in the reservoirs for the occurrence of high-impact floods. The flood wave travel time from the upper to middle catchment toward the end of the period after heavy rainfall over antecedent high soil moisture and high reservoir levels was of the order of 5 to 6 days. Hence an analysis based on precipitation outputs on a daily to weekly scale would also be important to track individual heavy rainfall events more specifically. Future research to understand the linkage between rainfall and hydrological mechanisms that cause flooding in this flow-regulated catchment is necessary to fully explain the increase in flood frequency.

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